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The Role of Stereopsis in Aviation: Literature Review

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14. ABSTRACT
Spatial awareness, or the ability to relate one's position to surrounding objects, is generally considered essential for military aviation. Depth perception is of particular importance, as many military aviation maneuvers rely on accurate judgment of distance to be performed with accuracy. The phenomenon of depth perception is a summation of both monocular and binocular cues. Monocular cues are psychological in nature and are learned skills based on life experiences. Stereopsis, on the other hand, is a binocular physiological cue that results from simultaneous fusion of two disparate retinal images that results in perception of a third dimension. The role of depth perception and stereopsis in flying has been a topic of interest since the birth of aviation medicine. This paper is a review of the literature on this topic. Based on the summations of the studies reviewed in this paper, it seems reasonable to conclude that stereopsis plays some role in judging depth in the course of performing aviation tasks. However, despite the extensive efforts invested in pursuing the role of stereopsis in aviation, a knowledge gap clearly exists to this day. Perhaps the biggest challenge has been the fact that in field studies it is difficult to isolate monocular and binocular cues, short of occlusive methods, which artificially alter the normal binocular field. Further, it is difficult to recreate environments where monocular cues may be subject to illusion. Perhaps a more viable approach is through three-dimensional rendering using computer displays. This would allow for control of monocular and binocular cues and each could be manipulated to assess the relative value in performance-specific tasks requiring judgment of depth. A future proposal will simulate a specific aviation-relevant task such as in-flight refueling, clearing fixed wing aircraft in flight, clearing rotary wing aircraft in flight, or call to landing for rotary aircraft to assess the benefit offered by stereopsis for performing the task.

15. SUBJECT TERMS
Stereopsis, monocular cues, binocular cues, aviation, spatial awareness, depth perception

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Spatial awareness, or the ability to relate one's position to surrounding objects, is generally considered essential for military aviation. While there are many cues to orient one's self to the environment, including proprioceptive and vestibular, interpretation of the visual surround is considered the strongest [1]. Depth perception is of particular importance, as many military aviation maneuvers, e.g., formation flying, initiation of flare, aerial refueling, obstacle/object avoidance, etc., rely on accurate judgment of distance to be performed with proficiency.

The phenomenon of depth perception is a summation of both monocular and binocular cues. Monocular cues, including retinal image size, linear perspective, motion parallax, and interposition (not an all-inclusive list), are psychological in nature and are learned skills based on life experiences. Thus, they can be improved with training, but are also prone to illusion [2,3]. In contrast, stereopsis is a binocular physiological cue that results from simultaneous fusion of two disparate retinal images that results in perception of a third dimension. Stereopsis develops early in life and is relatively immune to misinterpretation [4-6]. In this regard, monocular cues provide indirect information on depth that may be influenced by environmental or intrinsic factors, while stereopsis is a direct measurement that is not prone to illusion.

The role of depth perception and stereopsis in flying has been a topic of interest since the birth of aviation medicine. In 1919, Drs. Wilmer and Behrens [7] noted "the value of stereoscopic vision….is of great value in judging distance and landing…The importance of this qualification seems to grow greater as our experience increases." In a separate publication, Wilmer [8] stated, "The power of stereoscopic vision….is a great asset. This, added to good vision and muscle strength, aids greatly in judging distances, and therefore in making a good landing. For it is harder to make good landing than to do seemingly very difficult stunts in the air. Crashes due to faulty landing are most numerous." Howard [9] stated, "It is error in judgment of distance in landing a plane that has caused the great majority of deaths among cadet aviators." He further related a finding from the 1919 Manual of Medical Research Laboratory that 38 of 58 documented mishaps were during the landing phase of flight, although the binocular status of those fliers was unknown. Livingston [10] distinguishes between the monocular pilot (two eyes present, with loss of central vision in one eye) and the uniocular pilot (one eye present) and supports the notion of the former but not the latter. More recently, Diepgen [11] and Entzinger [12] have concluded that stereopsis is not required for flight safety, owing to the fact that other cues of depth are sufficient. However, as Entzinger astutely observes, "Although the nuance between 'require' and 'benefit from' may seem small, it is essential …The fact that monocular pilots can land aircraft successfully does not rule out the possibility that stereopsis is normally used as a depth cue in aircraft landing" [12].

Historically, there is evidence, albeit anecdotal, that supports the claim for the monocular aviator. Walter Hinchliffe was a Royal Air Force ace during WWI who lost his left eye in battle. He proceeded to have a successful civilian 10-year career as the chief pilot for Royal Dutch Airlines and established many commercial flying routes throughout Europe. William Guilfoyle [13] spent over two decades (1915-1939) as a pilot for the Royal Flying Corps after losing an eye to injury. He was awarded the Military Cross for gallantry in action in 1917 and retired with the rank of Air Commodore. Perhaps the most well known one-eyed pilot was Wiley Post, who was not only a pioneer in the field of aviation but supported the exploration of high-altitude flying and pressure suits. There are other examples that can be cited, e.g., Mick Mannock and James McCudden in WWI, Saburo Sakai in WWII; however, as previously stated, these are anecdotal cases that do not make a scientific case for the safety of flying with one eye. Interestingly,

Hinchcliffe, Mannock, McCudden, and Post all suffered fatal consequences in their aircraft from a variety of causes.

History has also presented evidence that flying without the perception of stereoscopic cues can result in mishap. Wilmer and Behrens [7] reported two cases of crashes during landing due to binocular disorders of the pilot. In the first event, the pilot suffered from paralysis of the superior oblique muscle in one eye and reported intermittent diplopia and difficulty judging distances while landing. The second example was due to a temporary disruption of the binocular system due to hypoxic exposure while flying at 15,000 feet for about an hour. The pilot lost engine power and made an immediate descent to the field. He initiated a flare maneuver when he judged his plane to be about 1 foot above the ground, when in reality he was about 15 feet; the plane stalled and crashed.

Nakagawara and Veronneau [14] described the crash of a Delta MD-88 on approach to LaGuardia airport in 1996. With the plane descending through 200 feet in heavy fog and rain, the pilot transitioned to visual references, as the glideslope indicator for the runway was not functional below this altitude. The airplane landed short, struck an approach light indicator that sheared off the main landing gear, and belly-landed on the runway. The National Transportation Safety Board investigation determined that "the probable cause of the accident was the inability of the captain, because of his use of monovision contact lenses (one eye corrected for far, one eye corrected for near), to overcome his misperception of the airplane's position relative to the runway during the visual portion of the approach" [15]. A post-accident examination revealed the pilot had substantially reduced stereopsis and was likely relying on monocular cues to judge distances. Although prohibited by the Federal Aviation Administration (FAA) based on first class medical standards which require that pilots have distant visual acuity of at least 20/20 in each eye [16], the pilot had flown with this lens modality for 6 years before the mishap and had an exemplary record. However, the circumstances during the mishap flight were ideal for creating visual illusions. First, the visibility was poor, which resulted in loss of detail and dimming of runway lights, both of which would give the illusion of being farther away and higher. Second, the approach was made over water, which offers fewer cues for judging altitude than would be available with detailed terrain. Third, the lights on the runway were spaced 150 feet apart, rather than 200 feet as was standard with most major runways. For a pilot who is accustomed to the 200-foot separation, this could lead to an overestimate of altitude by 70 feet if judging height based solely on the monocular cues.

Numerous formal studies have evaluated the role of stereopsis in landing performance by comparing binocular landings to landings performed under occlusive conditions. In 1935, Jongbloed [17] reported that he could find no differences in landings performed by experienced aviators under monocular and binocular conditions, although subjects reported a high level of apprehension when performing the task with one eye. Pfaffmann's study [18] of experienced Naval flight instructors flying a standard biplane trainer used bi-nasal occlusion to eliminate the binocular stereoscopic field, while maintaining the full visual field. He reported that removal of the binocular field created a tendency to flare too high and resulted in "missed" landings on 6 of 13 attempts versus misses on 1 of 12 attempts without occlusion. More recently, a National Aeronautics and Space Administration study [19] of experienced test pilots flying a T-33A jet trainer compared landing performance under binocular and monocular (using an occlusive patch) conditions. No differences in either lateral or longitudinal accuracy were observed; however, monocular approaches were flown with a greater rate of descent (i.e., steeper) and occluded subjects reported a greater cognitive workload. A limitation cited for all of these studies was the

fact that subjects were highly experienced pilots who might be expected to overcome unusual conditions with more competence than the typical pilot. Thus, several follow-on projects evaluated landing performance of low-hour civilian pilots flying a single-engine general aviation aircraft with and without occlusion. Lewis [20] reported a statistically significant improvement in landing accuracy under monocular conditions, although the authors could not offer any satisfactory explanation for this finding. In contrast to prior studies, there were no observed differences in the manner in which monocular approaches were flown, although pilots did report increased workload when performing monocularly. Grosslight [21] reported no differences in landing accuracy under monocular conditions, although he did find that monocular approaches were flown higher and steeper and were rated as more difficult by the subject pilots. The authors of these studies have generally concluded that the judgment of distance while landing is a combination of both monocular and binocular cues due to fact that, although landings could be performed under monocular conditions, the landing strategy was modified and subjects had to exert more cognitive effort to compensate for the loss of binocular input.

While the studies of landing under occlusive conditions provide some insight regarding the role of stereopsis when flying, they are only partially applicable to the interests of this paper for several reasons. First, these studies utilized normal subjects who were deprived of binocular vision on a sudden basis and had relatively little time to develop adaptive strategies. Second, with the exception of Pfaffmann's study, subjects were deprived of the full visual field, which has been shown to play a role in altitude maintenance during flight simulations [22]. Finally, the United States Air Force (USAF) does not accept a monocular individual for training in any aspect of aviation. Rather, the typical applicant with reduced (termed "defective") stereopsis exhibits monofixation syndrome. This condition, described by Parks [23] and Epstein [24], is characterized by a central suppression scotoma, which may be constant or intermittent, with peripheral fusion. Cover testing may reveal orthophoria, a well compensated phoria, a partially compensated phoria, or a small angle tropia (up to 8 prism diopters). Monofixation may also be associated with post-strabismus surgery; however, the USAF rarely grants such waivers due to an unpredictable post-operative course.

Surprisingly, a review of literature could find no studies that investigated flying capabilities of monofixating subjects versus subjects with normal stereopsis. Bauer [25] compared driving characteristics between 10 stereo normal subjects and 10 subjects with defective or missing stereopsis, defined as "no stereopsis on the Titmus test, or at most 'fly positive.'" Four aspects of driving performance were evaluated: (1) stopping distance from an object, (2) reversing into a parking space, (3) slalom driving, and (4) estimating the distance of oncoming traffic. The slalom test demonstrated superior performance by stereo normal subjects, while no significant differences were observed in the remaining three tasks.

Several studies have compared pilot training outcomes between stereo normal and stereo defective subjects. Kirschberg [26] used a modified Verhoeff device [27] at 3 meters to correlate levels of stereopsis with graduation rates among Royal Canadian Air Force pilot trainees in 1944. Subjects were placed into one of three categories: (1) good stereopsis – scored 6, 7, or 8 correct on 8 presentations of the modified Verhoeff; (2) average stereopsis – scored 3, 4, or 5 correct on 8 presentations; and (3) poor stereopsis – scored 0, 1, or 2 correct. Note that these results do not represent greater sensitivity of stereo threshold, but rather the number of presentations the subject correctly identified at a single threshold. Kirschberg's results showed no significant differences in graduation rates among the three groups, although anecdotally, they were highest among the candidates with poor stereopsis.

In 1993, Snyder [28] similarly performed a retrospective study of attrition rates from USAF Undergraduate Pilot Training (UPT) based on stereoscopic visual status. Three groups of subjects were identified: (1) applicants who passed the VTA (the USAF aeromedical standard for stereopsis), implying distant stereopsis of 25 arc sec or better; (2) applicants who failed the VTA, but passed the Verhoeff near stereopsis test at 16 arc sec; or (3) applicants who passed the Verhoeff test with unknown results on the VTA due to lack of documentation in medical records. Again, no significant differences in attrition rates were identified between any of the groups.

Lowry [29] compared UPT performance of 96 individuals waivered into USAF pilot training for defective stereopsis versus 8,907 subjects who met the stereopsis standard (25 arc sec or better on the Optec Vision Test 2300). The make-up of the defective stereopsis group was not specified; however, based on USAF waiver policy, these subjects demonstrated monofixation syndrome or a horizontal microtropia not exceeding 8 prism diopters. They also must have scored 60 arc sec on the Stereo Optical 9300 slide, often referred to as the AO Vectograph (this is a distance task that uses a polarized target to assess stereopsis), or scored 120 arc sec on the 9300 slide and 30 mm or less (better than 11 arc sec) on the Howard-Dolman depth perception test. Lowry graded UPT performance based on six aviation maneuvers, which will not be discussed in detail, but can be summarized as various formation maneuvers that occur within a distance of 600 feet or closer. Aggregate performance on these six maneuvers between cohorts was then statistically related based on five variables pertaining to the rate at which trainees gained and maintained proficiency on each maneuver. Five of the six variables showed a small, but statistically significant, difference between populations, with defective stereopsis subjects demonstrating inferior performance.

Waldroup [30] used a subset of subjects from Lowry's study to perform a similar comparison of stereo defectives (12 subjects) versus a control group of stereo normals (100 subjects) on an extended trail maneuver. This task requires the subject pilot to follow a lead plane through a series of aerobatic maneuvers at a distance of 500-1,000 feet behind the lead plane, and thus is considered to be a non-stereoscopic-dependent task. No statistical differences between populations were observed.

Findings from the Lowry study led USAF aeromedical policy makers to conclude that waiver criteria related to defective stereopsis were appropriate. However, given that Lowry's study demonstrated subtle differences in performance on stereo-based tasks, while Waldroup's study demonstrated no differences on non-stereo-based tasks, it was also concluded that relaxation of the waiver criteria could not be supported.

In 2009, Serkowski et al. [31] investigated UPT graduation rates for trainees with normal stereopsis versus those who had been admitted to training on a stereopsis waiver. He additionally included scores from the spatial subtest portion of the Multidimensional Aptitude Battery, which involves recognition of two-dimension rotated objects, as a second independent variable. Analysis of stereopsis status alone did not show any significant differences in UPT graduation rate. However, subjects who scored below the 5th percentile on the spatial subtest and also received a waiver to attend UPT with defective stereopsis were over four times more likely to fail UPT versus normal subjects (i.e., those with normal stereopsis and a spatial subtest score above the 5th percentile). This was a statistically significant finding; however, there was a large confidence interval due to the low sample size (three subjects), and it is unclear if the same result would be observed if more data were available.

DISCUSSION

Based on the summations of the studies reviewed in this paper, it seems reasonable to conclude that stereopsis plays some role in judging depth in the course of performing aviation tasks. Landing studies under occluded conditions demonstrate that the maneuver can be accomplished by monocular cues alone. However, the fact that subjects modified their strategy (higher and steeper descents) and experienced an increase in cognitive load suggests that some important piece of visual information was missing. The Delta mishap also provides evidence that landings can be successfully completed on a repeated basis using monocular cues; however, in the absence of stereopsis, conditions may render these cues inadequate. Furthermore, binocular viewing improves contrast sensitivity by 30%-40% over monocular viewing. Thus, a person without normal binocular function not only has the disadvantage of working without stereopsis, but also relies on monocular cues that are potentially diminished.

An important consideration when relating the role of stereopsis to any activity is the range of distances that provide useful stereoscopic information. There is substantial disagreement on this topic. Gregory [32] and Nagata [33] have suggested it may be as short as 10-20 feet, while Hirsch and Weymouth [34] represent the opposite end of the spectrum with an estimation of 1,200 meters. Typically, however, a distance of 100 to 500 meters is proposed [1,2,35,36]. If one accepts the middle ground, then stereopsis could certainly be expected to play some role in many aspects of aviation.

Just as there is poor agreement on the useful range of stereopsis, there is similar disagreement by international aviation governing bodies on what level of stereopsis is required to be considered "fit to fly," reported in Table 1. Currently, the USAF requires any aircrew involved in controlling or clearing the aircraft, out to 200 meters, to demonstrate 25 arc sec of stereo (although 60 arc sec is waiverable if the condition is considered to be stable). The U.S. Navy standard is 40 arc sec for aircrew in control of the craft with no allowance for waiver, while the U.S. Army requires 40 arc sec for all aircrew, regardless of crew position. Conversely, the Canadian Air Force and the FAA have no stereopsis requirements. Furthermore, the FAA allows pilots of all classes who have lost an eye to return to flying pending a 6-month adaptation period [37].

The origin of U.S. military standards for stereopsis can be traced back to recommendations of the Armed Forces National Research Council Vision Committee in the late 1940s [History 1944-1949 and Description of Organizational Structure (ADB237049); available to those with access at https://www.dtic.mil/DOAC/home.search]. However, it is unclear why the three branches of the U.S. military currently have different standards, considering that the committee and its findings were tri-service based. One might speculate that unique mission demands (e.g., aircraft carrier landings) may have influenced changes in policy over time. Alternatively, aeromedical policy changes may have been driven by mishaps. One example of this is a mid-air collision between two HH-60 helicopters over Nellis Air Force Base in 1998. Soon after that event, Air Force policy was modified to require all aircrew members who perform scanning duties (e.g., clearing wingtips) within 200 meters, regardless of crew position, to meet stereopsis standards. Prior to the crash, this requirement was only mandated of aircrew in control of the craft. Unfortunately, a complete understanding of the history of military medical policy is clouded by the fact that many of the historical documents detailing standards and changes to standards no longer exist or are buried so deeply in the archives they cannot be located.

Table 1. Stereopsis Requirements for Aircrew by Organization

Group	Crew Position	Stereopsis Requirement (arc sec)	Notes
U.S. Army	All aircrew	40	Will make exceptions on case-by-case basis
U.S. Navy	Pilot, weapons system operator, landing safety officer Other fixed wing aircrew, air traffic control	40 None	No waivers for any aircrew in control of aircraft
USAF	All aircrew, unless not involved in clearing of the airplane out to 200 m	25	Will waive up to 60 arc sec
FAA	Pilot	None	Will allow pilots to fly after losing eye provided a period of adjustment has passed (6 mo)
Canadian Air Force	Pilot	None	
Royal Air Force	Pilot Weapons system operator	120 None	

CONCLUSION

Despite the extensive efforts invested in pursuing the role of stereopsis in aviation, a knowledge gap clearly exists to this day. Perhaps the biggest challenge has been the fact that in field studies it is difficult to isolate monocular and binocular cues, short of occlusive methods, which artificially alter the normal binocular field. Further, it is difficult to recreate environments where monocular cues may be subject to illusion. Although not explicitly stated, one would presume that monocular landing studies were not performed under adverse visual conditions owing to safety concerns for study participants.

Perhaps a more viable approach is through three-dimensional rendering using computer displays. This would allow for control of monocular and binocular cues and each could be manipulated to assess the relative value in performance-specific tasks requiring judgment of depth. A future proposal will simulate a specific aviation-relevant task such as in-flight refueling, clearing fixed wing aircraft in flight, clearing rotary wing aircraft in flight, or call to landing for rotary aircraft to assess the benefit offered by stereopsis for performing the task.

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